Laser Interaction
and Related Plasma Phenomena

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LASER DRIVEN PLASMA INSTABILITIES AT MODERATE LASER IRRADIANCES

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ABSTRACT

A systematic investigation is in progress on Second Harmonic (SH) and Three-Half Harmonic ($3\omega/2$) emission generated by the interaction of a 3 ns 1.064 μm Nd:YAG laser beam with underdense plasmas produced from thin plastic targets at irradiances up to 5×10^{13} Wcm^{-2}. 2-D time resolved imaging of the interaction region in SH light has been performed for a detailed characterization of SH radiation sources in the plasma. The onset of a SH emission regime dominated by Filamentation Instability is clearly evidenced by these images of the interaction region and confirmed by the anomalous scaling of SH power with incident laser power. The dependence of SH emission on target position has also been measured revealing an unexpected behaviour which we believe is linked to the effect of local beam geometry on Filamentation Instability growth rate mechanisms. A simple model of $3\omega/2$ emission is discussed which takes in account refraction of Two Plasmon Decay (TPD) produced electron waves. This model shows a strong dependence of $3\omega/2$ spectra on longitudinal density gradients. In contrast with 2ω, transverse density gradients do not contribute appreciably to $3\omega/2$ emission. We report on a new experiment performed to test the model and the effective reliability of $3\omega/2$ as a diagnostic tool to estimate electronic plasma temperature.

INTRODUCTION

Laser driven plasma instabilities are presently under extensive experimental and theoretical investigation world-wide due to the role they play in ICF experiments[1]. Great effort is being devoted in order to achieve control of these processes mainly by optimizing irradiation parameters through the introduction of laser beam smoothing techniques[2,3]. Among the large number of laser driven plasma instabilities, particular attention has been devoted to Filamentation Instability (FI). Incidentally it should be pointed out that the local increase of laser intensity produced by FI can give rise to interaction conditions suitable for instabilities to take place whose intensity threshold is higher than the average nominal intensity.

Our group is involved in collaborative experiments at Rutherford Appleton Laboratory (RAL), UK and at Ecole Polytechnique, France, to study some of these instabilities at intensity exceeding 10^{15} Wcm^{-2}. Particularly in the RAL experiment we study those effects in laser interaction with long-scalelength preformed coronal plasmas. In this experiment was proved that suitable beam smoothing techniques allow to control filamentation as well as stimulated Brillouin and Raman scattering[4]. A parallel study is performed at IFAM at lower laser intensity, up to 5×10^{13} Wcm^{-2}. This intensity is still relevant to ICF and as been demonstrated to be able to excite several instabilities directly or via filamentation. Moreover at these levels of laser power a much larger number of shots can be produced during a single experiment, resulting in more accurate measurements.

In this paper we present recent experimental results obtained at moderate intensity. The experimental method simply consists in the direct irradiation of thin plastic foils with laser pulses whose duration and intensity on target allow the expanding plasma to become underdense early in the pulse. In particular the paper reports on the analysis of SH and 3ω/2 scattered radiation, which is one of the most direct approaches to plasma instabilities. A direct link between Filamentation Instability (FI) and 2w emission from underdense plasmas is not yet experimentally established strong evidence has been provided[5,6,7] which supports such correlation.

We discuss recent experimental investigation on forward 2ω emission from laser interaction with underdense plasmas. These measurements follow our previous analysis on side scattered SH radiation[7,8] and another interesting experiment[9] where filaments were artificially created into a plasma in order to study the mechanism of 2ω generation. Our measurements on forward emission clearly show that SH strongly emerges from the plasma self emission in presence of filamentation and filaments are the main source of 2ω light. There is a definite confirmation that SH generation from underdense plasmas is very sensitive to the presence of transverse gradients (both density and field gradients). On the other hand, 3ω/2 spectra are mostly influenced by longitudinal density gradients as those produced by exploding foils. This observation was already considered in the interpretation of previous spectra[10] and is further supported by recent spectroscopic studies. They were performed using a new technique designed to detect in a single shot two separate spectra of 3ω/2 light emitted from both sides of the original target plane.

EXPERIMENTAL SET UP

A schematic diagram of the experimental set up with the main diagnostics for the study of SH and 3ω/2 emission is shown in Fig.1. A 3 ns (FWHM) 1.064 μm Nd:YAG (0.7 Å

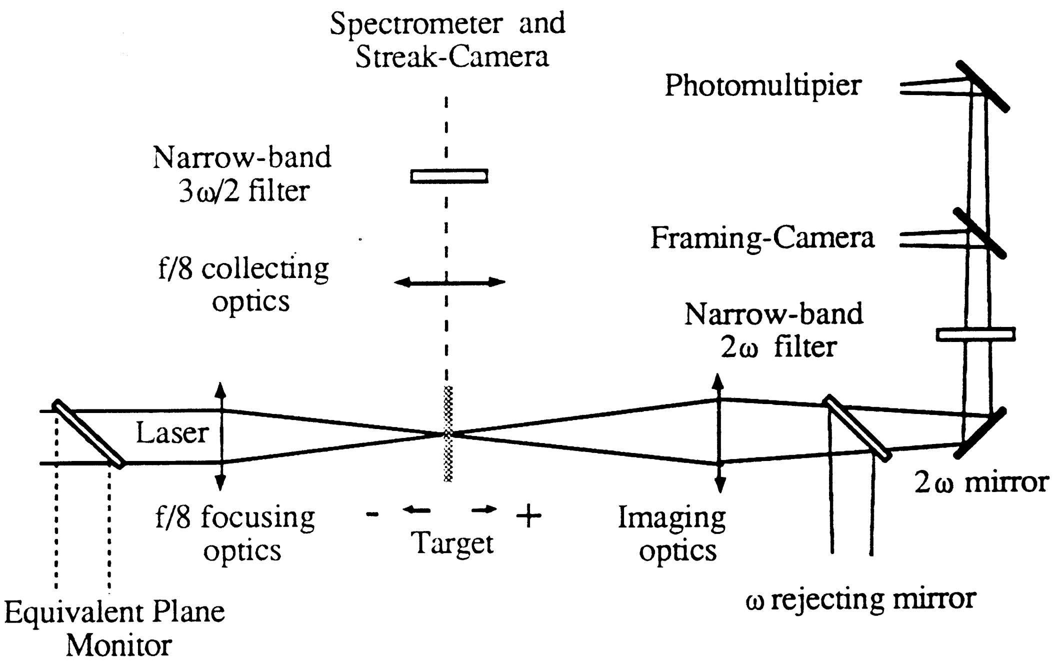

Fig.1 Schematic set up for 2ω and 3ω/2 measurements from laser produced plasma.

spectral band-width) laser beam was focused with an f/8 optics in a 60 μm focal spot on thin plastic (FORMVAR) targets whose thickness ranged from 0.1 to 1.8 μm. The laser intensity on target was varied between 5×10^{11} and 5×10^{13} Wcm^{-2}. The cross section of the laser beam in the focal region was monitored by an equivalent plane imaging optics.

A visible spectrometer coupled to a streak-camera was used for time resolved spectroscopy of $3\omega/2$ radiation. The temporal resolution was 30 ps while the overall spectral resolution was 3 Å. A 120 ps gate-time visible Framing-Camera (FC)[11] allowed 2-D time resolved imaging of the interaction region in SH light to be performed. A 80X magnified image of the plasma was produced on the input window of the FC whose spatial resolution is approximately 100 μm. Therefore the limit to the overall resolution in the plasma (≈ 2 μm) was finally set by optical aberration eventually present the imaging optics. Photomultiplier tubes and diode detectors coupled to suitable narrow-band interference filters were employed for energy measurements of scattered light.

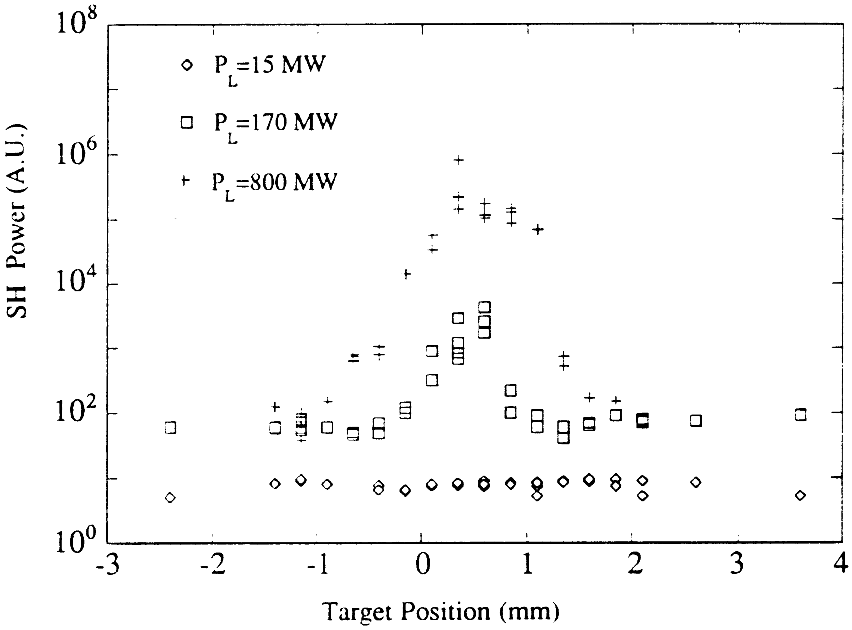

Fig.2 Forward Second Harmonic power as function of target position along the beam axis relative to the laser beam waist. Laser power levels were 15 MW, 170 MW and 800 MW and the target thickness was 1μm.

RESULTS AND DISCUSSION

Second Harmonic measurements

The graph of Fig.2 shows SH power as function of target position with respect to the laser beam waist for three different laser power levels. A spectral window of 30 Å centred on the exact $2\omega_L$ angular frequency, ω_L being the laser angular frequency, was selected by an interference filter. The transmitted light was detected by a photomultiplier tube. For laser power of 15 MW, corresponding to an intensity at the beam waist of approximately 5×10^{11} Wcm^{-2}, no dependence of the detected radiation was found on target position within the explored range. On the contrary an incident laser power of 170 MW resulted in a strong dependence of SH emission on target position with a maximum at approximately +600 μm from the nominal position of the laser beam waist.

Similar but enhanced behaviour was observed for laser power of 800 MW where the maximum emission was an order of magnitude higher than in the case of 170 MW laser

power. Speculation on the shift of the maximum SH emission from the nominal focus requires a discussion on the methods used to determine the position of the focus itself. However this analysis is not relevant to the aim of this paper and is reported elsewhere[12].
It should be noted that the signal detected for marginal target positions, (typically for distances greater than 1.5 mm from the position of maximum SH emission), as well as the whole curve at the lowest laser power level, has to be attributed to bremsstrahlung radiation at the same frequency as the SH. Such conclusion is supported by comparing these measurements with analogous ones performed by tilting the interference filter. As a result of this tilting the spectral region allowed by the filter was shifted by the amount required to exclude narrow-band SH light from the detected spectral window. On the contrary the spectrum of bremsstrahlung radiation can be considered flat for a relatively large wavelength range compared to the SH band-width. Therefore, the contribution of bremsstrahlung radiation to the detected signal in both conditions is expected to remain fairly constant. In fact we observed that in condition of maximum SH emission, a tilt of the interference filter by 30° reduced the amplitude of the photomultipier signal by a factor of thousand. On the other hand a small signal variation was observed with tilted filter for marginal target positions or low laser power thus confirming the above assumption.

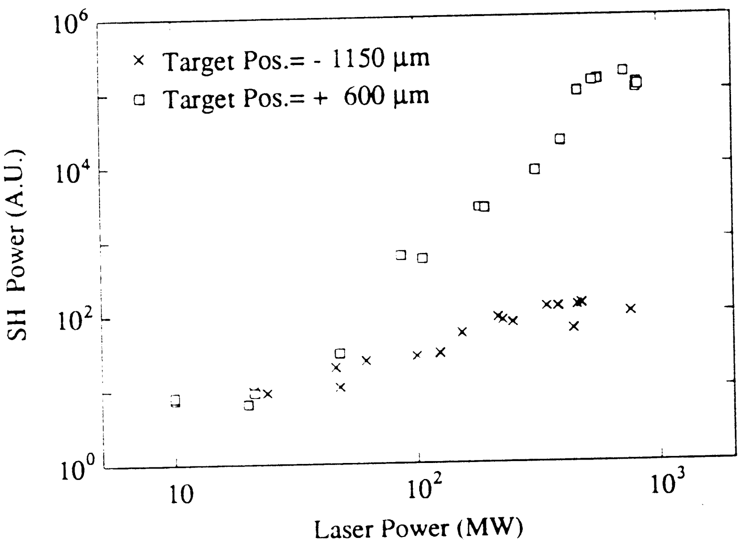

Fig.3. Forward Second Harmonic power as function of laser power for a 1μm target in the position of maximum emission and in a marginal position at -1.15 mm.

The most evident feature of the plots shown in Fig.2 is that SH emission clearly dominates over bremsstrahlung by up to three orders of magnitude. In addition we notice that an increase in the level of SH emission up to two orders of magnitude was detected for target displacement of approximately 200 μm. This value is definitely smaller than the overall depth of focus of our focusing optics which was measured to be approximately 600 μm. Therefore it is evident that some mechanism takes place which strongly modifies the laser intensity distribution generated by the focusing optics. This conclusion is supported by the dependence of SH emission on incident laser power. Fig.3 shows a plot of SH emission as function of laser power in a range from 10 MW to approximately 1GW with the target in position of maximum emission and, for comparison, in a marginal position.

In the range of laser power P_L between 0.1 and 1 GW, SH power P_{SH} scales approximately as the third power of P_L. On the other hand a sub-linear scaling of P_{SH} with laser power is measured for target in a marginal position. As stated above, most of the light collected at marginal target positions is due to bremsstrahlung radiation. This fact can explain the weak dependence of this curve on incident laser power. On the contrary, the more than quadratic scaling of P_{SH} with target in the position of maximum conversion efficiency can only be explained if extra processes are included which can "boost" the non-linear SH conversion efficiency. It is well known that ponderomotive and thermal effects can drive laser focusing processes in the laser-plasma interaction region. On the other hand another indirect experimental evidence of Filamentation Instability has already been established in our previous analysis of side scattered SH radiation in an underdense plasmas[7].

A more direct evidence of filamentary structures in our experiment was provided by the Framing Camera time resolved images. Fig.4 shows a time resolved 120 ps gate-time image of the interaction region in SH light at the time of the peak of the 3 ns laser pulse. The incident laser power was 800 MW and the target was 1μm thick and was set in the position of maximum SH conversion efficiency. The same timing was used to obtain a large number of images, including those shown in Figs. 5b and 6b.

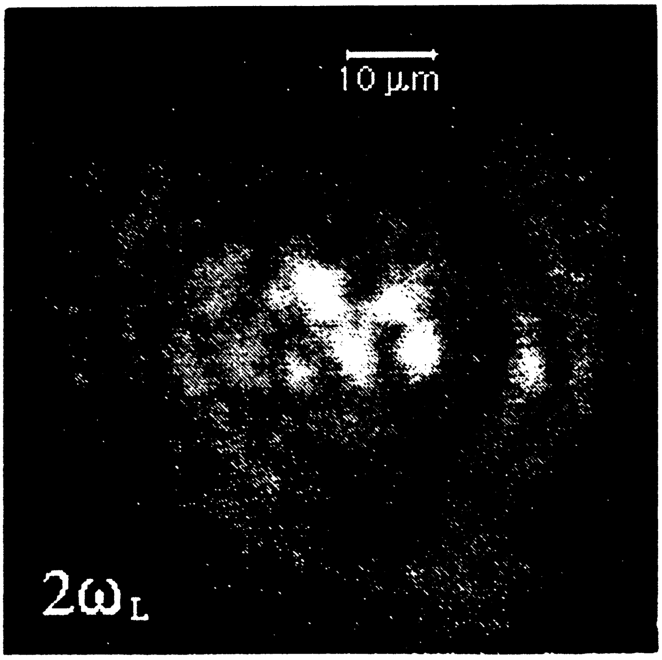

Fig.4 Time resolved Framing Camera image of the interaction region in Second Harmonic light with target in the position of maximum SH emission.

This image clearly shows that SH emission comes from small circular regions, approximately 5 μm in diameter, which are well localized in the centre of the spot. The size of these structures is fairly reproducible shot by shot while their number and position change unpredictably. A simple question arising now is whether this pattern can simply be correlated to the intensity distribution in the laser beam or it is the result of more complex processes, probably initiated by laser beam inhomogeneities but ultimately due to plasma instabilities. A simple comparison between SH time resolved images and laser beam intensity distribution in the focal spot can give a valuable indication of the kind of coupling regime we are dealing with.

Equivalent Plane (EP) imaging was employed to study laser beam intensity distribution in the focal spot. An infrared (Kodak I.R. 4143) film was used to take EP images at different positions along the beam axis. Fig.5 shows a comparison between an EP image of the focal spot and another time-resolved FC image of the interaction region with the targetin the same position of maximum SH conversion efficiency. Not only laser beam non-uniformities, but also optical aberrations of the focusing optics may contribute to the intensity distribution of Fig.5a. For this reason the clear difference between pictures of Fig.5a and Fig.5b cannot be considered as a conclusive evidence of the action of FI. Much more significant is that i) the size of the 2ω filamentary sources in Figs.4, 5b and several others pictures obtained in the same condition is close to the theoretical size expected for FI maximum growth; ii) 2ω images varied considerably shot by shot, while the ω equivalent plane images did not.

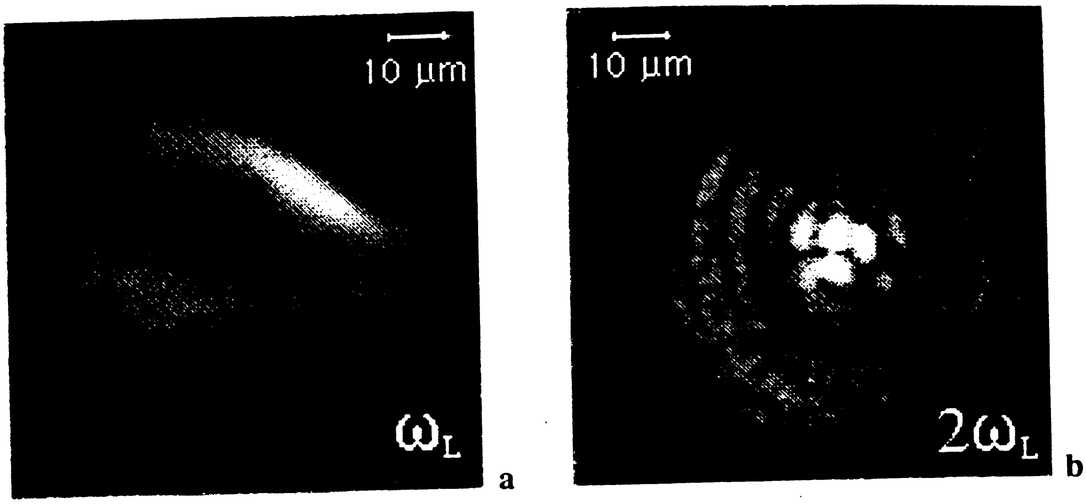

Fig.5 a)Equivalent Plane Image of laser focal spot at the waist of the f/8 main focusing optics and b)Framing Camera image of the interaction region in Second Harmonic light taken with the target at the same position of the equivalent plane image.

Therefore the laser intensity non-uniformities by itself cannot explain the SH source distribution nor the shot to shot variation evidenced by FC time resolved images. Filamentation process has to be included to explain the localized SH emission we observe in our experiment relatively to the target position of maximum of SH conversion efficiency. It should be emphasized that this filamentation dominated regime of SH emission seems to be confined in a narrow region of target positions around the maximum of Fig.2. as evinced from the following results. Fig.6 shows a set of images analogous of that of Fig.5 but taken with target at approximately -400 µm which, according to Fig.2 is still in the interval of high SH conversion efficiency but far from the maximum. In this case the laser intensity distribution shown by the EP image of Fig.6a is affected by the astigmatism of the beam. Although graphically attractive, the resemblance in shape of these two images should be carefully examined before drawing any conclusion as already pointed out in the case of Fig.5. In fact optical aberrations of the EP imaging system could introduce *ad hoc* changes in the laser focal spot intensity distribution. In addition the comparison of images is based on the corrispondence of the EP position in the case of Fig.6a and target position in the case of Fig.6b. Since large variations in the exact shape of the EP images is found for variation of the plane position on a 100µm scale, a comparison of the shape of the two images would require the knowledge of the exact location of 2ω sources in the plasma. And the accuracy on this measurement is limited by the depth of focus of the 2ω imaging channel.

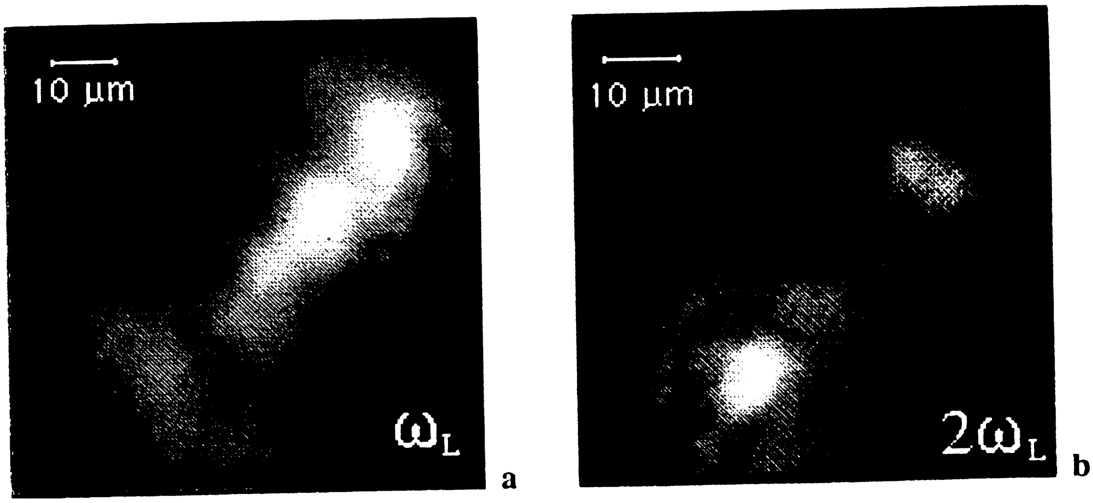

Fig.6 a)Equivalent Plane Image of laser focal spot 400 µm before the beam waist of the f/8 main focusing optics and b)Framing Camera image of the interaction region in Second Harmonic light taken with the target at approximately the same position of the equivalent plane image.

On the contrary it is important to point out that the pattern shown in this case by time resolved images was found to be highly reproducible shot by shot as already observed in the case of EP images.Therefore in this condition forward SH emission has to be attributed largely to intensity non-uniformities already present in the laser beam. Moving the target closer to the position of maximum SH emission there is a transition to a filamentation dominated regime.

The intermediate regime with SH emission but with low level of filamentation has been also investigated with measurements of SH power versus laser power. The different scaling of SH power with incident laser power typical of this regime is illustrated by Fig.7 compared with that relative to the filamentation dominated regime shown in Fig.3. Although the overall behaviour of these two plots is similar, the rate of growth of P_{SH} with P_L is different in the two cases. In contrast with the more than quadratic scaling of P_{SH} with P_L evidenced in the plot of Fig.3, the growth of P_{SH} in Fig.7 is closer to a quadratic regime.

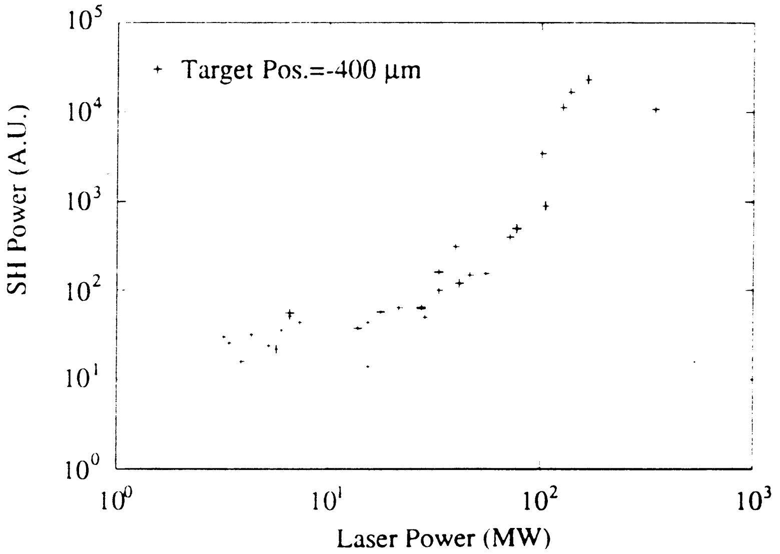

Fig.7 Forward scattered Second Harmonic power as function of laser power for a 1μm target in the same position as Fig.6.

This comparison suggests that relative position between laser beam focusing configuration and plasma density or temperature profile are not suitable in this intermediate regime, for an efficient growth of filamentation processes. Second Harmonic emission in this regime can therefore be attributed to transverse electric field gradients at the boundary of the laser beam waist as shown in Fig.6, and density gradients which originate from these intensity non-uniformities. We observe that the average laser intensity in the focal spot doesn't vary appreciably from Fig.5 to Fig.6. This suggests that it is possible to reduce the effect of FI at a given intensity on target by choosing appropriate target position in the region surrounding the beam waist.

Three-half harmonic measurements

$3\omega/2$ harmonic emission consequent on Two Plasmon Decay (TPD) can be a useful tool to diagnose plasma temperature. According to the present understanding, 3/2 harmonic is generated by the coupling (Raman-like scattering) of laser photons with TPD plasmons excited in the $n_c/4$ layer by laser light itself. ω_L and $3\omega/2$ photons can propagate through this layer without strong refractive effects. For this reason spectral features of coupling plasmons can be directly inferred from the analysis of $3\omega/2$ light . TPD produced plasma waves are frequency shifted from $\omega_L/2$ value according to

$$\delta\,\omega = 3\,k_L\,\chi\,v_e^2\,/\omega_L$$

where k_L is the wave-vector of the laser photon, χ is the component of the plasmon in the direction of k_L reduced by $k_L/2$. Consequently $3\omega/2$ light should be frequency shifted by an amount proportional to the plasma temperature, the coupling coefficient being simply related to the matching condition in k-space. In terms of the detection angle θ with respect to the laser beam axis

$$\delta\,\omega = (3\,k_L^2\,v_e^2\,/\omega_L)\,((8/3)^{1/2}\cos\theta - 3/2).$$

Experimental measurements give indeed very broadened spectra, due to the strong refraction of plasmons before they couple. Plasmon frequency cannot be simply related to their wavevector because density gradients present in the plasma can affect the χ parameter[10,13]. The observed $3\omega/2$ spectrum is red or blue shifted with respect to the above formula whether density gradient component along the beam is negative or positive respectively.

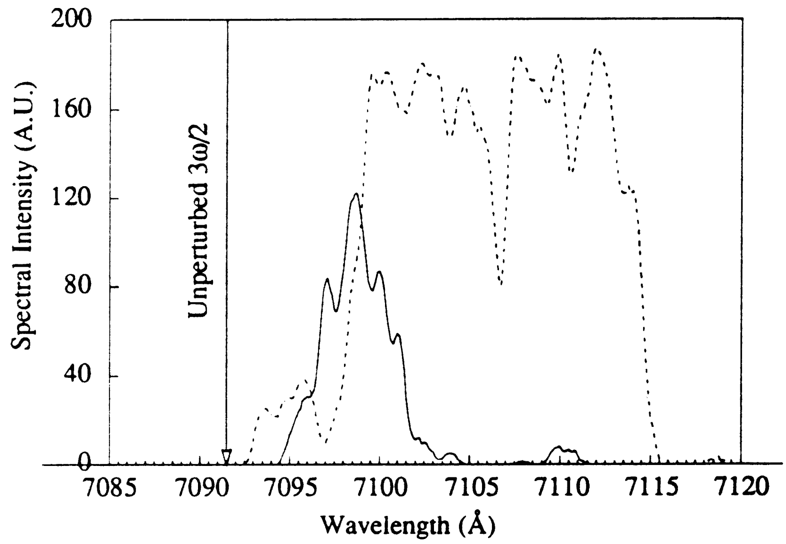

Fig.8 Densitometric traces of $3\omega/2$ spectra relative to the two plasma regions with opposite gradients along the beam axis. The plasma was produced from of 1.1 μm thick plastic target at an irradiance of 7×10^{12} Wcm^{-2}.

Two plasma regions with opposite gradients along the beam axis are present in plasmas produced by irradiating thin solid targets. Spectra of $3\omega/2$ emitted normally to the laser beam axis by these two regions were detected in the same shot. Due to the spiky temporal emission of our laser spectra with both spatial and temporal resolution could be recorded. The laser-plasma interaction region was imaged out on the entrance slit of a spectrometer, with the laser axis parallel to the slit axis. The two different spectra resulting in the output plane were in turn imaged on the entrance slit of the streak camera which was fully open. In this configuration the temporal resolution was limited to the duration of a single spike. On the other hand a partial spatial resolution could be achieved. Pairs of spectra produced from different spikes were well separated by the streak.

In Fig.8 densitometric traces of two simultaneous spectra are reported. From the unperturbed $3\omega_L/2$ a shift of about 8 Å can be estimated for unpropagated plasmons. This value leads to an electron temperature of approximately 250 eV which is consistent with previous measurements[13]. This preliminary result is the first attempt to use spatial resolution in order to evaluate plasma temperature from broad $3\omega/2$ spectra. The technique, although promising, needs to be refined and to be supported by a more accurate modeling.

CONCLUSION

Our recent results on 2ω and $3\omega/2$ harmonics improve the capability of diagnose laser-plasma interactions in conditions of interest for ICF. In particular SH emission was found to be very suitable to detect and control Filamentation Instability. In this context the pure evaluation of FI intensity threshold seems not to be sufficient, because also the position of the target respect to the beam waist seems to be critical. In a range of position corresponding to few focal depth we observed three distinct regimes. At marginal position of the target respect to the waist the SH emission, if any, was merged into the plasma self-emission. At intermediate position, where laser intensity on target was close to its nominal maximum, SH level rose up to values definitely higher than continuum. In this latter condition the structure of the SH sources was found to be strictly related to the original non-uniformities of the laser beam. Closer to the beam waist SH jumped up more than three order of magnitude above the continuum, the SH source pattern was very unstable shot by shot and there was clear evidence for Filamentation Instability.

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